

TRIPLE PRODUCT ASYMMETRIES IN Λ_b AND Ξ_b^0 DECAYS

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The LHCb experiment is capable of studying four-body decays of the b -flavored baryons Λ_b and Ξ_b^0 to charmless final states consisting of charged pions, kaons, and baryons. We remark on the search in such modes for CP-violating triple product asymmetries and for CP rate asymmetries relative to decays involving charmed baryons.

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I Introduction

In Ref. [1] we presented a general discussion for T-odd triple product (TP) asymmetries in four-body decays of strange, charmed, and beauty mesons, focusing on genuine CP-violating asymmetries. Earlier studies of such asymmetries in B meson decays to two charmless vector mesons have been made in Refs. [2–4]. The LHCb experiment can extensively study four-body decays of the b -flavored baryons Λ_b and Ξ_b^0 into charged pions, kaons, and baryons [5]. In the present paper we make some observations relevant to the search for CP asymmetries in such decays. Such asymmetries are expected in charmless final states but not in charmed final states, which thus provide an important control.

We discuss general features of Λ_b and Ξ_b^0 decays to charmless final states in Section II. Aspects of such decays relevant to CP asymmetries are noted in Sec. III, while we specialize to four-body decays to charmless baryons and charged pions and kaons in Sec. IV. Resonant subsystems of four-body final states are discussed in Sec. V. We conclude in Sec. VI.

II General features of charmless Λ_b and Ξ_b^0 decays

Transitions of b -flavored baryons to charmless final states are governed by two main subprocesses, which we will denote “penguin” and “tree”. The penguin amplitudes effectively lead to a $b \rightarrow s$ transition when the decay changes strangeness ($|\Delta S| = 1$) and $b \rightarrow d$ for $\Delta S = 0$. The $\Delta S = 0$ penguin amplitude P is approximately λ times that (P') for ($|\Delta S| = 1$), where $\lambda = \tan \theta_C$ is the tangent of the Cabibbo angle. The tree subprocess T is $b \rightarrow u\bar{u}d$ for $\Delta S = 0$, while for $|\Delta S| = 1$ (T') it is $b \rightarrow u\bar{u}s$, with amplitude λ relative to T . From studies of B meson decays and low-multiplicity Λ_b decays (see [6] and references

therein) one can expect $|\Delta S| = 1$ processes to be dominated by penguin amplitudes and $\Delta S = 0$ processes to be dominated by trees.

III Aspects relevant to CP asymmetries

In order to observe a direct CP asymmetry, one needs two amplitudes with different weak phases and different strong phases to interfere with one another. The asymmetry will be maximal when the amplitudes have comparable magnitudes and relative weak and strong phases each as close as possible to 90° .

For the tree and penguin amplitudes governing charmless b -flavored baryon decays, the relative weak phases are dominated by the large weak phase of the Cabibbo-Kobayashi-Maskawa matrix element V_{ub} : $\arg(V_{ub}) \equiv -\gamma \simeq -67^\circ$ [7]. The relative strong phases are not predictable *a priori* but can be varied in multibody decay by varying the masses of subsystems over the profiles of Breit-Wigner resonances. The relative magnitudes of tree and penguin amplitudes are in inverse proportion for $|\Delta S| = 1$ and $\Delta S = 0$ amplitudes, giving the possibility of a closer match between tree and penguin strength for one ΔS case or the other.

The study of CP asymmetries in a proton-proton collider such as the CERN Large Hadron Collider (LHC) is handicapped by the potentially unequal production rates of particles and antiparticles. For this reason (and for cancellation of different detector sensitivities to particles and antiparticles) it is useful to study CP-violating triple product asymmetries. An asymmetry A_T (as defined in Ref. [1]) can arise without CP violation as a result of final-state interactions, but should be equal to the asymmetry \bar{A}_T for the corresponding antiparticle decay if CP is conserved, so the difference

$$\mathcal{A}_T \equiv \frac{1}{2}(A_T - \bar{A}_T) \quad (1)$$

provides a measure for CP violation. Triple product asymmetries in two- and three-body decays of polarized Λ_b have been discussed in Refs. [8–11].

Another way of avoiding to a large extent uncertainties due to unequal production rates of bottom baryons and antibaryons may be achieved by measuring differences between CP rate asymmetries in charmless decays and in decays involving charmed baryons. Differences in detector sensitivities to particles and antiparticles may be minimized by choosing final states with identical particles in charmless and charmed decays, taking into account their different momenta.

IV U-spin in four-body decays involving π^\pm and K^\pm

We summarize accessible four-body charmless final states of Λ_b involving protons, Σ^+ hyperons, charged pions, and charged kaons in Table I. Also shown are final states of $\Xi_b^0 = bsu$. We include Σ^+ because it is related to the proton by a U-spin reflection $d \leftrightarrow s$. A similar transformation interchanges Λ_b and the lower-lying Ξ_b^0 (neglecting small configuration mixing in the Ξ_b^0). The Σ^+ decays to $n\pi^+$ (almost impossible to identify) and $p\pi^0$ (requiring a detector to reconstruct neutral pions).

Table I: Four-body charmless final states involving a proton, a Σ^+ , charged pions, and charged kaons, in decays of $\Lambda_b = bud$ and $\Xi_b^0 = bsu$.

| Decaying particle | $ \Delta S $ | Amplitudes | Final state |
|-------------------|--------------|------------|---------------------------|
| Λ_b | 1 | T', P' | $pK^-\pi^+\pi^-$ |
| | | | $pK^-K^+K^-$ |
| | | | $\Sigma^+\pi^-K^+K^-$ |
| | 0 | T, P | $\Sigma^+\pi^-\pi^+\pi^-$ |
| | | | $pK^-K^+\pi^-$ |
| | | | $p\pi^-\pi^+\pi^-$ |
| Ξ_b^0 | 1 | T', P' | $\Sigma^+\pi^-K^+\pi^-$ |
| | | | $pK^-\pi^+K^-$ |
| | | | $\Sigma^+\pi^-\pi^+K^-$ |
| | 0 | T, P | $\Sigma^+K^-K^+K^-$ |
| | | | $pK^-\pi^+\pi^-$ |
| | | | $pK^-K^+K^-$ |
| | | | $\Sigma^+\pi^-K^+K^-$ |
| | | | $\Sigma^+\pi^-\pi^+\pi^-$ |

CP (or T) violating triple-product asymmetries \mathcal{A}_T may be formed from each of these final states and four-body final states in corresponding antibaryon decays. (CP violating triple-product correlations have already been investigated experimentally in charmed particle decays [12–14] where they are expected to be very small in the standard model [15].) In the case of two identical particles (here, K^-K^- or $\pi^-\pi^-$) they are distinguished from one another by calling particle number 1 the one with the higher momentum.

CP rate asymmetries for pairs of processes in which initial and final states are obtained from each other by a U-spin reflection $d \leftrightarrow s$ have been shown to have equal magnitudes and opposite signs in the U-spin symmetry limit [16–18]. This property has been confirmed experimentally in two-body B^0 and B_s decays [19] and in phase-space-integrated three-body B^+ decays [20]. We will now show that, while similar relations hold also for phase-space-integrated CP rate differences in four-body decays of bottom baryons, such relations are not obeyed by the triple product CP asymmetries \mathcal{A}_T .

Consider, for instance, $\Lambda_b \rightarrow p(\vec{p}_1)K^-(\vec{p}_2)\pi^+(\vec{p}_3)\pi^-(\vec{p}_4)$ in the Λ_b rest frame, $\Sigma_i \vec{p}_i = 0$. We define a T-odd triple product asymmetry

$$A_T \equiv \frac{\Gamma_{\Lambda_b}(C_T > 0) - \Gamma_{\Lambda_b}(C_T < 0)}{\Gamma_{\Lambda_b}(C_T > 0) + \Gamma_{\Lambda_b}(C_T < 0)} \equiv \frac{\text{Cor}_{\Lambda_b}}{\Gamma_{\Lambda_b}}, \quad (2)$$

where $C_T \equiv \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$. In order to test CP violation we compare this asymmetry with a corresponding asymmetry in the CP conjugate process $\bar{\Lambda}_b \rightarrow \bar{p}(-\vec{p}_1)K^+(-\vec{p}_2)\pi^-(-\vec{p}_3)\pi^+(-\vec{p}_4)$, where the minus signs follows by applying parity to the three-momenta,

$$\bar{A}_T \equiv \frac{\Gamma_{\bar{\Lambda}_b}(C_T < 0) - \Gamma_{\bar{\Lambda}_b}(C_T > 0)}{\Gamma_{\bar{\Lambda}_b}(C_T > 0) + \Gamma_{\bar{\Lambda}_b}(C_T < 0)} \equiv \frac{\text{Cor}_{\bar{\Lambda}_b}}{\Gamma_{\bar{\Lambda}_b}}. \quad (3)$$

Here $-C_T \equiv -\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$ is the triple product of momenta for charge-conjugate particles.

The difference

$$\mathcal{A}_T \equiv \frac{1}{2}(A_T - \bar{A}_T) \quad (4)$$

provides a measure for CP violation. A nonzero asymmetry \mathcal{A}_T ,

$$\frac{\text{Cor}_{\bar{\Lambda}_b}}{\Gamma_{\bar{\Lambda}_b}} \neq \frac{\text{Cor}_{\Lambda_b}}{\Gamma_{\Lambda_b}}, \quad (5)$$

may follow from a CP asymmetry in partial rates,

$$\Gamma_{\bar{\Lambda}_b} \neq \Gamma_{\Lambda_b}, \quad (6)$$

and/or from a CP asymmetry in triple-product correlations,

$$\text{Cor}_{\bar{\Lambda}_b} \neq \text{Cor}_{\Lambda_b}. \quad (7)$$

Now consider the decay $\Xi_b^0 \rightarrow \Sigma^+(p_1)\pi^-(p_2)K^+(p_3)K^-(p_4)$ which is related to $\Lambda_b \rightarrow pK^-\pi^+\pi^-$ by a U-spin reflection, $d \leftrightarrow s$. Using the unitarity of the CKM matrix,

$$\text{Im}(V_{ub}^*V_{us}V_{cb}V_{cs}^*) = -\text{Im}(V_{ub}^*V_{ud}V_{cb}V_{cd}^*), \quad (8)$$

one may show that the two CP rate asymmetries have equal magnitudes and opposite signs in the U-spin symmetry limit [17, 18]:

$$\Gamma_{\bar{\Lambda}_b} - \Gamma_{\Lambda_b} = -[\Gamma_{\Xi_b} - \Gamma_{\bar{\Xi}_b}]. \quad (9)$$

A similar relation holds for corresponding triple product correlations,

$$\text{Cor}_{\bar{\Lambda}_b} - \text{Cor}_{\Lambda_b} = -[\text{Cor}_{\Xi_b} - \text{Cor}_{\bar{\Xi}_b}]. \quad (10)$$

These two equations do not imply a relation between $\mathcal{A}_T(\Lambda_b)$ and $\mathcal{A}_T(\Xi_b)$, namely between $\text{Cor}_{\bar{\Lambda}_b}/\Gamma_{\bar{\Lambda}_b} - \text{Cor}_{\Lambda_b}/\Gamma_{\Lambda_b}$ and $\text{Cor}_{\Xi_b}/\Gamma_{\Xi_b} - \text{Cor}_{\bar{\Xi}_b}/\Gamma_{\bar{\Xi}_b}$. That is, separate opposite sign relations, (10) for CP asymmetries in triple product correlations and (9) for corresponding decay rate asymmetries, do not imply a similar relation for their ratios. As mentioned, the requirement of normalized CP violating triple product asymmetries follows from uncertainties in relative production rates of baryons and antibaryons. These uncertainties may be largely avoided by studying CP rate asymmetries relative to decays involving charmed baryons.

V Subsystems in four-body decays

Resonant subsystems in multibody final states offer the possibility of controlling (or at least varying over a known range) the relative strong phases of amplitudes, as long as the resonances are produced differently by tree and penguin processes. (See, for example, Refs. [21, 22].) We shall show this to be the case for the processes of interest.

Motivated by a picture of hadronization as due to quark-pair creation as a QCD string stretches and undergoes fragmentation [23], one can draw graphs illustrating the formation

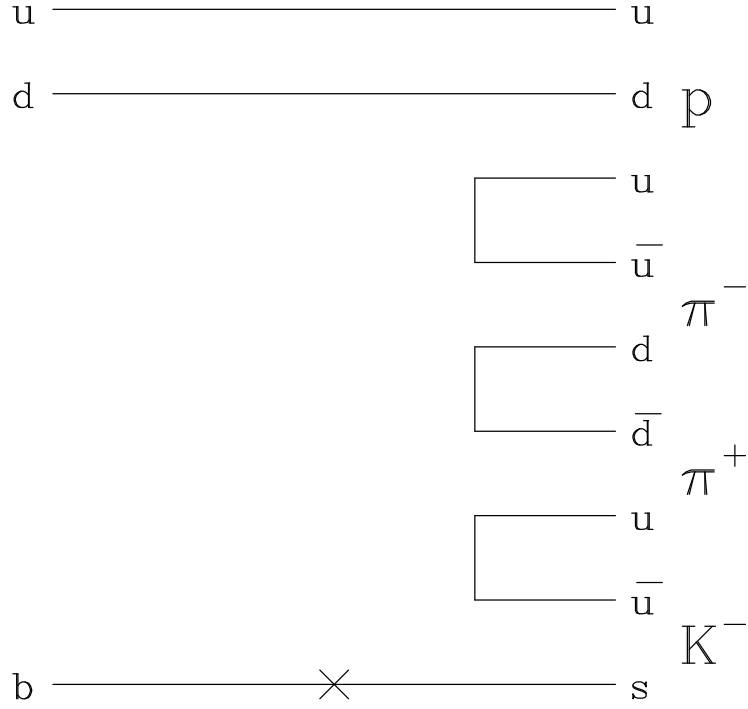


Figure 1: Example of fragmentation graph for penguin $b \rightarrow s$ process in $\Lambda_b \rightarrow p\pi^-\pi^+K^-$.

Table II: Fragmentation of $\Lambda_b = bud \rightarrow sud$ into $pK^-\pi^+\pi^-$ or permutations such that any two adjacent hadrons can form a resonance, shown for the $b \rightarrow s$ penguin amplitude. The same eight orderings are allowed for the $b \rightarrow s\bar{u}u$ amplitude.

| Final state | Resonance (example) | | |
|------------------|---------------------|---------------|----------------|
| | 12 | 23 | 34 |
| $p\pi^-\pi^+K^-$ | N^{*0} | ρ^0 | K^{*0} |
| $\pi^-p\pi^+K^-$ | N^{*0} | Δ^{++} | \bar{K}^{*0} |
| $K^-p\pi^+\pi^-$ | Λ^{*0} | Δ^{++} | ρ^0 |
| $K^-p\pi^-\pi^+$ | Λ^{*0} | N^{*0} | ρ^0 |
| $\pi^+\pi^-pK^-$ | ρ^0 | N^{*0} | Λ^{*0} |
| $\pi^-\pi^+pK^-$ | ρ^0 | N^{*0} | Λ^{*0} |
| $K^-\pi^+p\pi^-$ | \bar{K}^{*0} | Δ^{++} | N^{*0} |
| $K^-\pi^+\pi^-p$ | \bar{K}^{*0} | ρ^0 | N^{*0} |

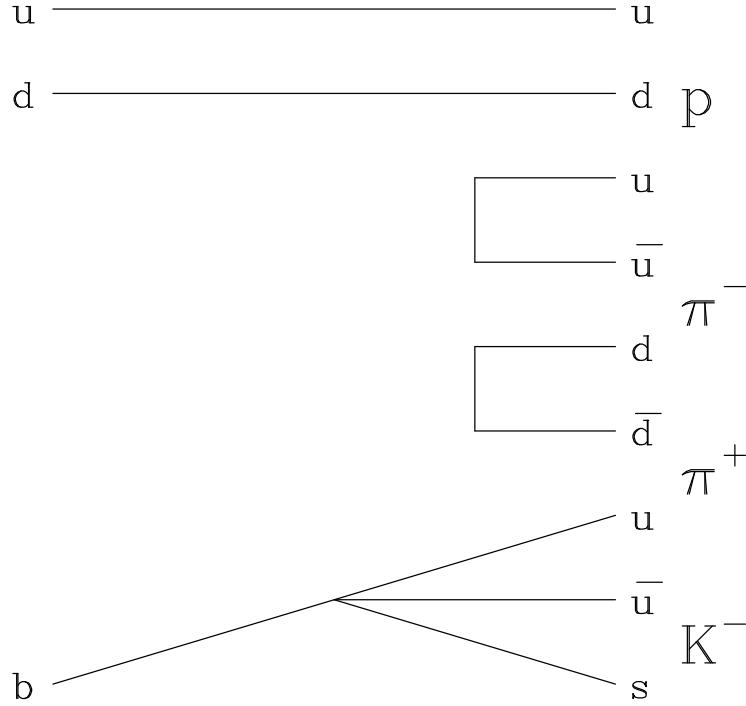


Figure 2: Example of fragmentation graph for tree $b \rightarrow s \bar{u} u$ process in $\Lambda_b \rightarrow p \pi^- \pi^+ K^-$.

of resonant subsystems in four-body charmless decays of Λ_b and Ξ_b^0 . Let us take the $\Delta S = 1$ penguin process $b \rightarrow s$ in $\Lambda_b \rightarrow p K^- \pi^+ \pi^-$ as an example. One draws all possible ways of fragmenting sud into $p K^- \pi^+ \pi^-$, such that any two adjacent hadrons can form a resonance. Such a graph is shown in Fig. 1. The results are shown in Table II.

The resonant subsystems one expects in this final state are thus N^{*0} (a generic $I = 1/2$ or $3/2$ nucleon resonance), ρ^0 or any $\pi^- \pi^+$ resonance, \bar{K}^{*0} and its excitations, and any of numerous $K^- p$ resonances Λ^{*0} such as $\Lambda(1520)$ [24].

We now consider resonant subsystem production by tree amplitudes. In this case the basic subprocess for $\Delta S = 1$ is $b \rightarrow u \bar{u} s$, which requires one less light $q \bar{q}$ pair produced from the vacuum than the penguin subprocess $b \rightarrow s$ to yield the same final state. Consequently, the profile of resonance excitations by the tree amplitude necessarily will differ from that of the penguin amplitude. An example for the final state $p \pi^- \pi^+ K^-$ is shown in Fig. 2. In this case the most notable difference from Fig. 1 is the excitation of $\pi^+ K^-$ resonances. This turns out to be so for all eight orderings listed in Table II.

In Ref. [1] one could discuss 4-body spinless meson decays with much greater specificity if they were dominated by quasi-two-body channels such as a pair of vector mesons. If quasi-two-body final states dominate Λ_b decays, helicity-amplitude decompositions may shed light on CP-violating triple products. Any of the (12) and (34) pairings in Table II could be expected to exhibit quasi-two-body behavior. Natural sets of variables exist (e.g., [2, 25]) for parametrizing such decays.

VI Concluding remarks

We have discussed triple-product CP asymmetries in four-body decays of Λ_b and Ξ_b^0 to a proton or a Σ^+ hyperon, charged pions, and charged kaons. Decays involving a proton are most likely to be observed and interpretable when the final-state hadrons experience resonant substructure. In that case, scanning across a Breit-Wigner resonance in the effective mass of a two-body subsystem is guaranteed to produce a final-state phase varying over an interval of nearly 180° . In order for this phase to contribute to a CP asymmetry, the interfering penguin and tree amplitudes have to produce the resonance with different initial phases. The different production topologies for penguin and tree amplitudes strongly suggest this will be the case.

Decays involving a Σ^+ are related by a U-spin reflection to corresponding decays with a proton. Integrated CP rate asymmetries in these pairs of processes are predicted to have approximately equal magnitudes but opposite signs. Performing such direct tests at the LHC requires knowledge of ratios of production rates for bottom baryons and bottom antibaryons and of ratios of detector sensitivities for low-lying baryons and antibaryons. Uncertainties due to unequal production rates of bottom baryons and antibaryons may be avoided to a large extent by measuring differences between CP rate asymmetries in charmless decays and in decays involving charmed baryons.

One can extend the present discussion to final states involving two baryons and an antibaryon, such as $p\bar{p}pK^-$ and $p\bar{p}p\pi^-$. Fragmentation diagrams resemble those of Figs. 1 and 2, except that instead of a $d\bar{d}$ pair in the middle of the chain, one has an antidiquark–diquark pair $[\bar{u}\bar{d}][ud]$. The mass distributions are likely to be dominated by low-mass $p\bar{p}$ enhancements (e.g., $X(1835)$ [24]), as observed in B decays [26], so quasi-two-body groupings $(p\bar{p})(pK^-)$ or $(p\bar{p})(p\pi^-)$ are likely to be useful.

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